

Characterization of Caribbean Meso-Scale Eddies

José M. López

Department of Marine Sciences, University of Puerto Rico,
P.O. Box 9013, Mayaguez, Puerto Rico 00681-9013
phone: (787) 832-4040 x 5229 fax: (787) 834-8025 email: jlopez@uprm.edu

Jorge E. Corredor

Department of Marine Sciences, University of Puerto Rico,
P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: j_corredor@cima.uprm.edu

Julio M. Morell

Department of Marine Sciences, University of Puerto Rico,
P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: j_morell@cima.uprm.edu

Jorge E. Capella

Department of Marine Sciences, University of Puerto Rico,
P.O. Box 908, Lajas, Puerto Rico 00667-908
phone: (787) 899-2049 fax: (787) 899-3838 email: jcapella@caribe.net

Fernando Gilbes

Department of Geology, University of Puerto Rico,
P.O. Box 9001, Mayaguez, Puerto Rico 00681-9001
phone: (787) 834-7620 fax: (787) 265-6340 email: gilbes@cacique.uprm.edu

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LONG-TERM GOALS

Our long-term goal is to improve predictivity of physical, biogeochemical and optical properties of Eastern Caribbean waters under the influence of mesoscale eddies and their interaction with regional features (i.e. massive riverine discharge). Expected outcomes from this research include the capacity to infer subsurface properties and processes as well as their temporal and spatial evolution utilizing remotely acquired surface observations. This program will contribute to the development of infrastructure for marine research and education at the University of Puerto Rico. A particular expectation is the recruitment and training of graduate students who will focus their graduate research in current scientific issues attuned with the above expressed goals.

SPECIFIC OBJECTIVES

- Characterization of the horizontal and vertical physical/biogeochemical gradients and their interaction with optical properties across fronts, eddy structures and massive river plume discharges in the Eastern Caribbean Sea.

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- Explore empirical relationships between remotely sensed ocean color and sea surface height and ocean properties.

APPROACH

We have implemented a series of research cruises, code named CaVortEx (for Caribbean Vorticity Experiment) to carry out observations of the optical and physical structure and upper water column biogeochemistry of mesoscale eddies. Eddy distribution and displacement were followed using the output from 1/16° operational global Naval Research Laboratory (NRL) Layered Ocean Model (NLOM), near real time altimetry data, SeaWiFS and MODIS imagery. During research cruises we obtained continuous flow surface records of temperature (T), salinity (S) and chlorophyll a (Chl-a), vertical sections of these variables plus apparent optical properties using the Nv-shuttle underwater undulating towed data acquisition system. Discrete vertical profiles of physical (T, S), chemical (dissolved oxygen, nutrients, colored dissolved organic matter and inherent (a, b, c) and apparent (R_{RS} , T, K_z) optical properties were obtained. Current structure across fronts and eddies was characterized by means of ship-lowered (LADCP) current profiler. These studies also included assessment of rates of biomass accumulation, primary production and photosynthetic efficiency using radiocarbon incubations on-deck to determine photosynthetic parameters and fast repetition rate fluorometry (FRRF) in situ.

WORK COMPLETED

In FY 07, we conducted data analysis and synthesis of CaVortEx 6 Oceanographic Cruise which was completed in Sep 2006 to document the optical, physical, chemical and biological properties of contrasting water masses across eddy boundaries and to characterize the biogeochemical transformations arising from boundary interactions. Experiments were designed to test model results which indicate that, under the influence of meso-scale eddies, primary frontal boundaries undergo spatial modifications resulting in enhancement of vertical and horizontal flux, and of biogeochemical activity and that “eddy pumping” similarly results in enhanced biological production. Such interactions generate variability of inherent optical properties in response to changes in particle abundance and size distribution resulting from enhanced biological production, phytoplankton community successions, and increased release, production and transformation of CDOM.

RESULTS

A. CaVortEx 6 Oceanographic Cruise

Cruise CaVortEx 6 was completed in Sept 2006 undertaken with the purpose of further characterizing cyclonic and anti-cyclonic eddies in the central Caribbean. Specific goals were:

- To quantify “eddy pumping” effects by cyclonic eddies in the Caribbean, and,
- To characterize fine scale eddy structure by means of a towed undulating instrument package
- To characterize eddy entrainment of the Orinoco River plume and upwelling waters off the north coast of South America

We present measurements of bio-optical and physical properties made in a mesoscale cyclonic eddy structure shown in maps of sea surface height anomaly (SSHA) in the Eastern Caribbean Sea region from space-based altimetry. Cruise tracks and sampling schemes (CTD and XBT casts) were designed to test model results which indicate that, under the influence of mesoscale eddies, primary frontal boundaries may undergo spatial modifications resulting in enhancement of vertical and horizontal flux and biogeochemical activity. Hydrographic and optics package casts as well as undulating underwater data collection systems were employed. Color maps of meridional sections of the inherent optical property, beam attenuation (beam c), and chlorophyll- a fluorescence overlaid on temperature and salinity data depict a rich pattern of associated vertical and horizontal features including fresh water entrainment, isopycnal doming, non chlorophyll- a particulate attenuation zones and cross pycnocline transport. We explore whether, for these cross sections, in-situ and remote ocean color data support the view that anti-cyclonic circulation results in increased biomass accumulation in contrast to cyclonic circulation. A cruise track overlaid on an image of Sea Surface Height Anomaly (SSHA) is presented below.

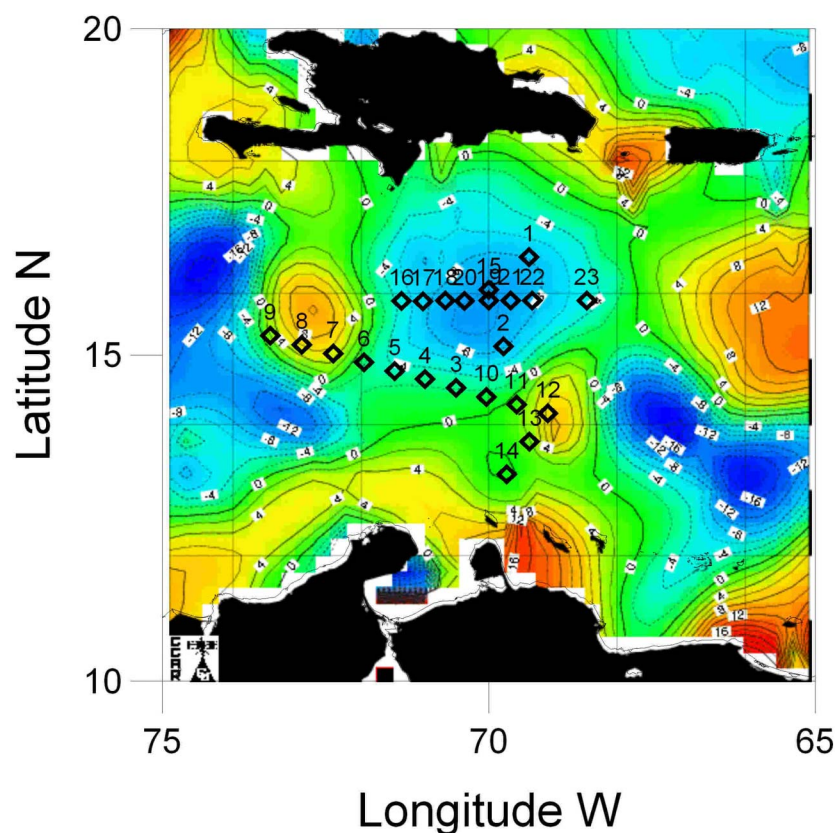


Figure 1. CaVortEx 6 cruise track map overlaid on an image of SSHA for Sept 4 2006 showing station sections across cyclone and anticyclones.

Cavortex 6: Station Track

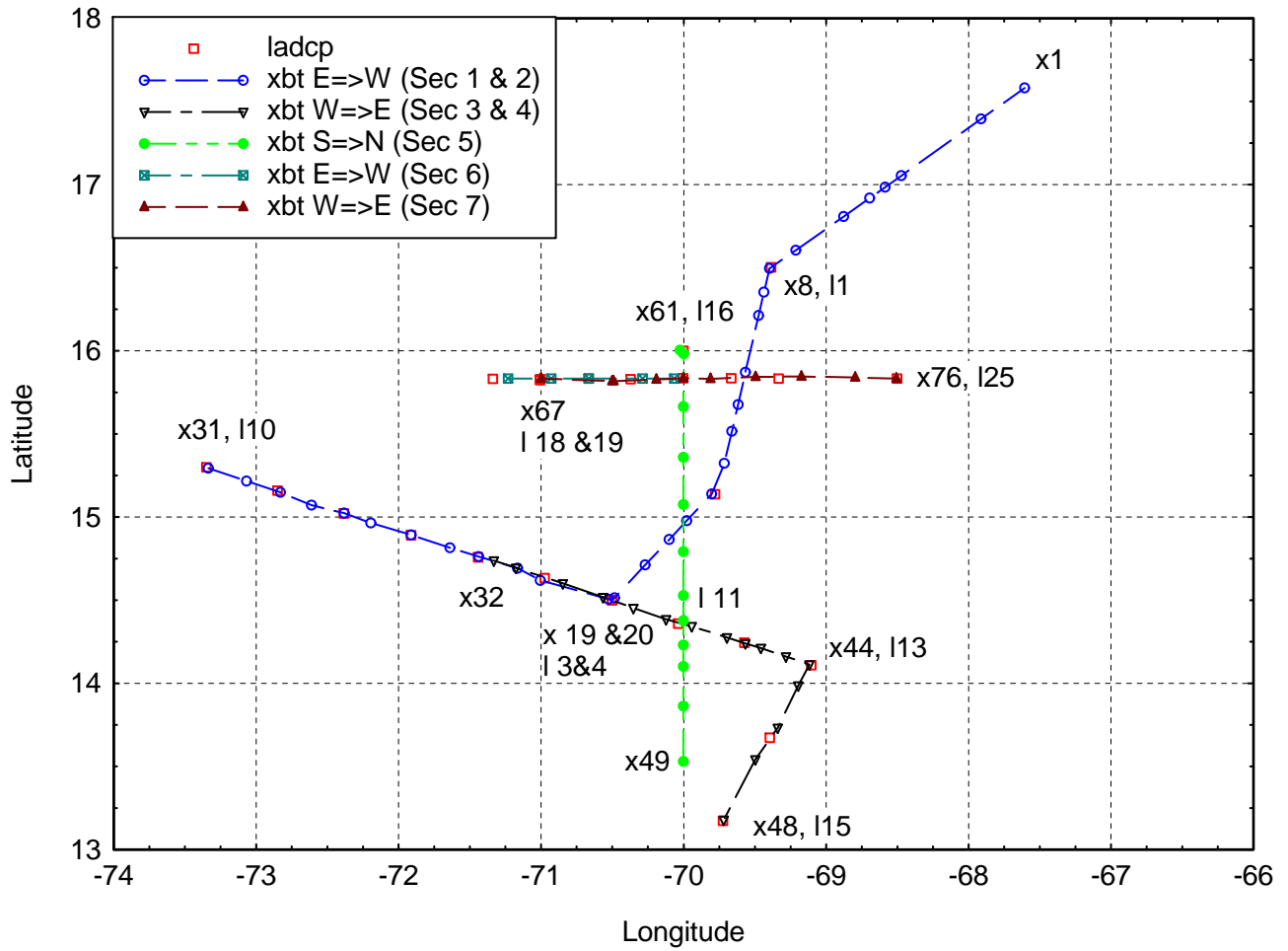


Figure 2. Summary plot of station positions (lat/lon) of Lowered Acoustic Doppler Current Profiler (LADCP) cast and Expendable Bathythermograph (XBT) East-West and North-South sections within a region bounded by 13 to 18 deg N and -74 to -67 E.

B. High Resolution, Undulating Underwater Data Collection System results

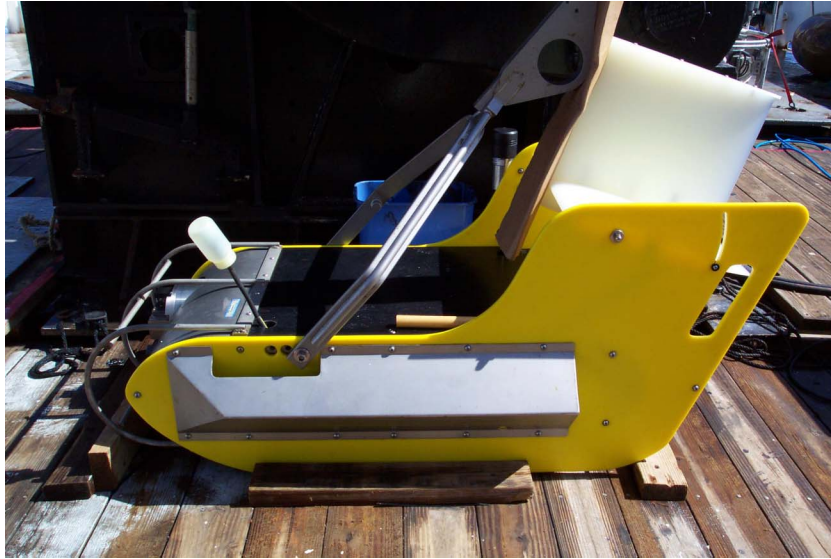


Figure 3. Shown on deck, real-time underway data collection system NuShuttle Undulating Underwater Vehicle carrying CTD_Fluorometer, Fast Repetition Rate Fluorometer (FRRF) and Beam-c (660) transmissometer.

High Resolution, Undulating Underwater Data Collection System transects were sampled across a cyclonic and anti-cyclonic eddies as well as zones devoid of mesoscale features identifiable by satellite altimetry. Typically, the oscillation range and frequency followed for these runs results in 75 oscillations per 30 nautical miles at depth ranging from 15 to 90m. Upper water column structure observed through this approach documented excursions of the upper thermocline, halocline and subsurface chlorophyll maxima expected to occur in eddy regions. Moreover, data indicates the widespread occurrence (both within and outside of eddies) of vertical excursions in the 5 to 20 meter range with apparent wavelengths ranging from 4 to 15 km. Often these coincided with localized enhancement of chlorophyll and or decreases in beam attenuation coefficient (c_{670}).

C. Results for CTD and XBT Casts At 30 Km Horizontal Resolution

- Independent Temperature measurement profiles were made by CTD and XBT casts at nominally 30km horizontal intervals across a cyclonic eddy with nominal vertical resolution of less than 1 m. Meridional plots of eddy cross section from the interpolated data at this resolution show evidence of shallow doming of isotherms (Thermocline Eddy).

D. 1km Horizontal Resolution From Underwater Undulating Data System

- A much more complex physical and optical structure is revealed by the 1 km horizontal resolution (< 1 m vertical) data obtained with the Undulating Underwater Data Collection System across the same transect of the Cyclonic eddy.

- Upper water column structure observed through this approach documented intricate excursions (high rugosity of the surfaces) of the upper thermocline, halocline and subsurface chlorophyll maxima beyond that expected from “classical” eddy doming alone.
- The ratio of Beam c to Chlorophyll-a suggests surface accumulation of non-chlorophyll carbon in the cyclone core.
- Data indicates the widespread occurrence (both within and outside of eddies) of vertical excursions in the 5 to 20 meter range with apparent wavelengths ranging from 4 to 15 km. Often these coincided with localized enhancement of chlorophyll and or decreases in beam attenuation coefficient (c_{660}).

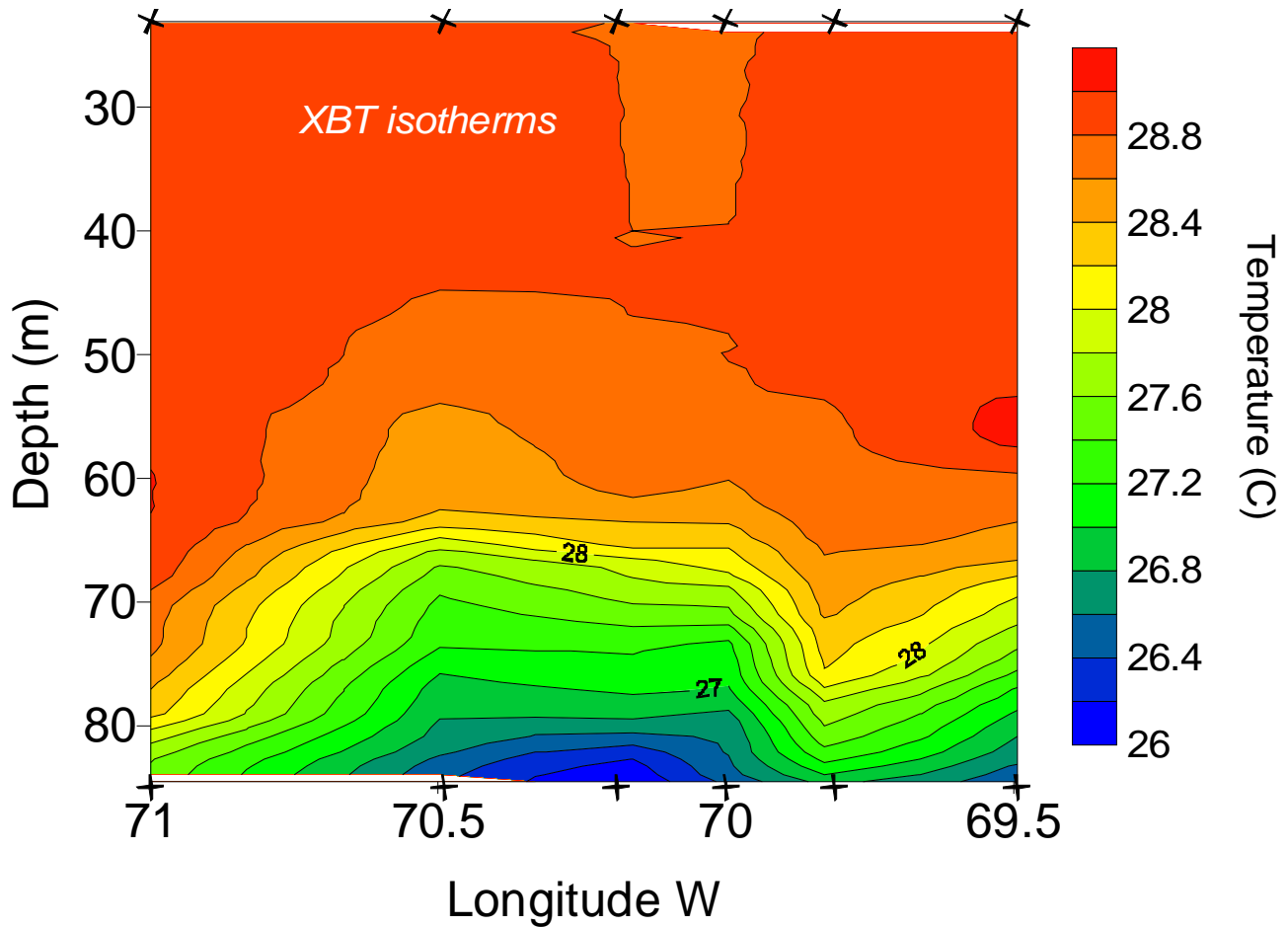


Figure 4. XBT-derived isotherms in upper 90m in cross section from 69.5 to 71.0 W reveals upward doming due to upwelling in cyclone. Black crosses at bottom and top of panel mark position of 6 xbt casts from which data is interpolated.

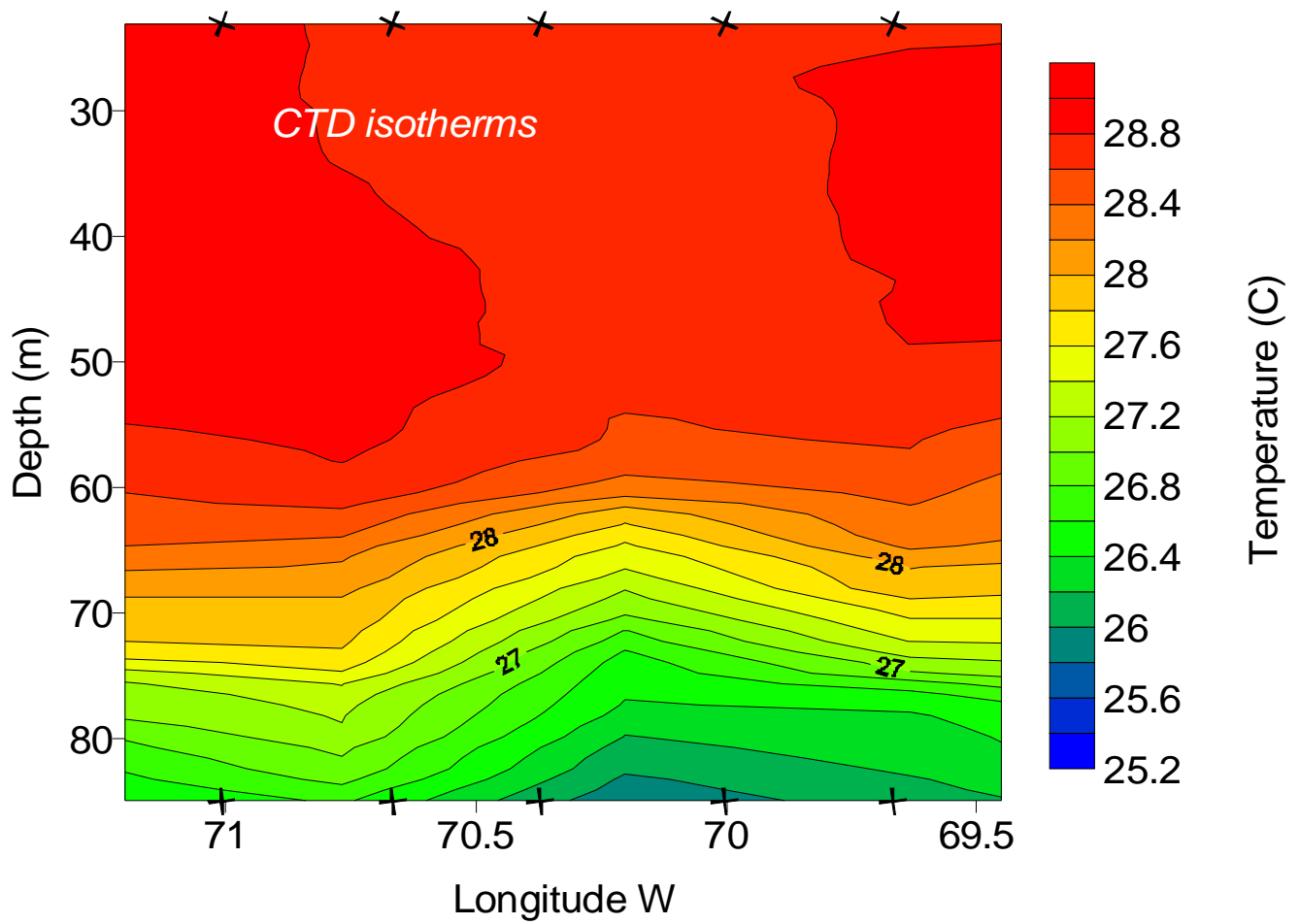


Figure 5. CTD-derived isotherms in upper 90m in cross section from 69.5 to 71.5 W suggests upward doming due to upwelling in cyclone. Resolution is poorer than XBT's. Black crosses at bottom and top of panel mark position of 5 CTD casts from which data is interpolated.

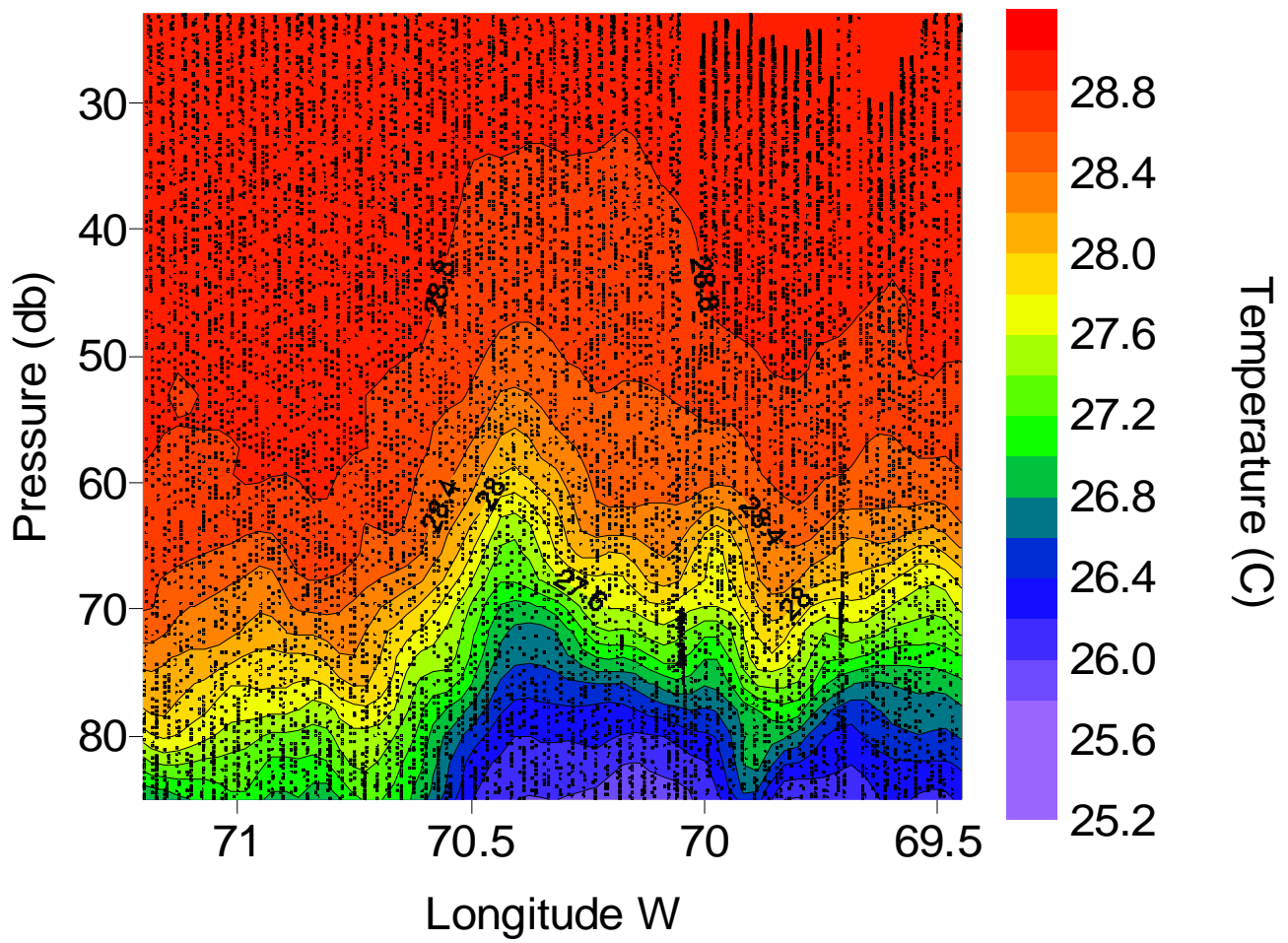


Figure 6. NuShuttle-derived isotherms in upper 90m in cross section from 69.5 to 71.5 W reveals rich detail of upward doming due to upwelling in cyclone. Black dots illustrate the high density of continuous sampling by Underwater Undulating Vehicle.

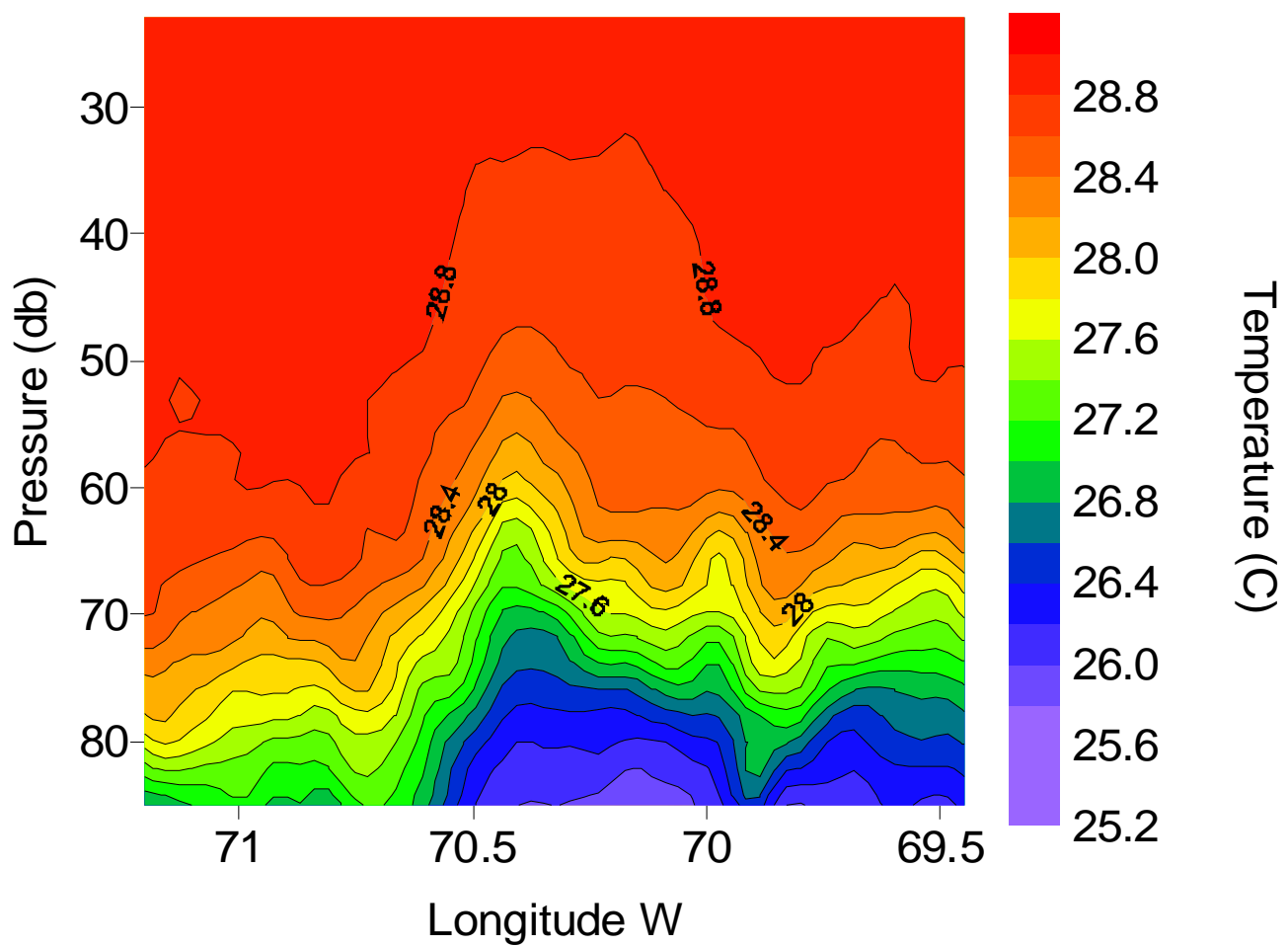


Figure 7. Same as Figure 6 with black dots removed to permit clear view of rich detail show upwelling of 25 deg C water with doming of isotherms of 15 to 25 m excursion.

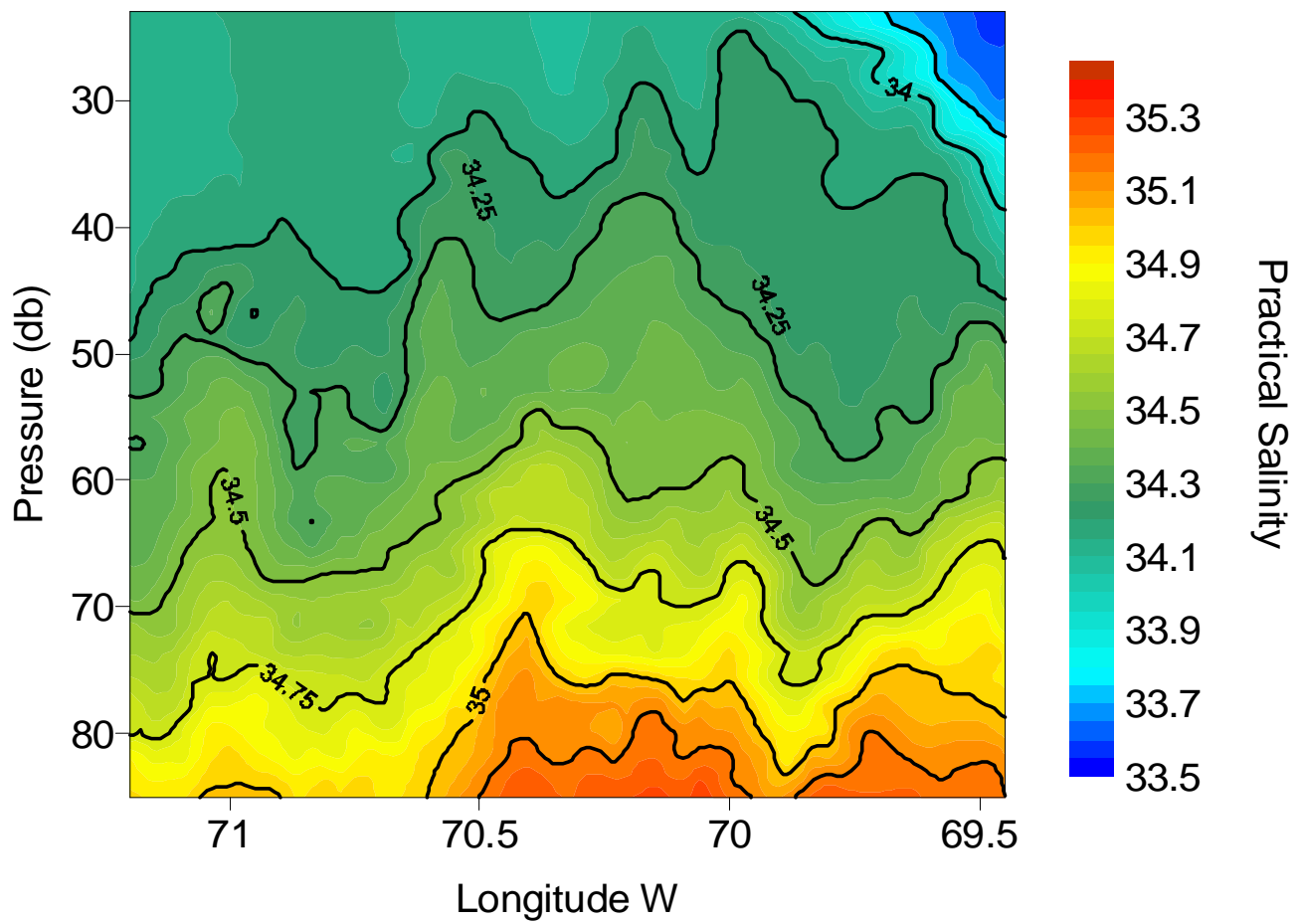


Figure 8. UUV- derived isohaline contours in upper 90m in cross section from 69.5 to 71.0 W reveals upward doming due to upwelling in cyclone of 35 psu water and 33.5 psu in surface.

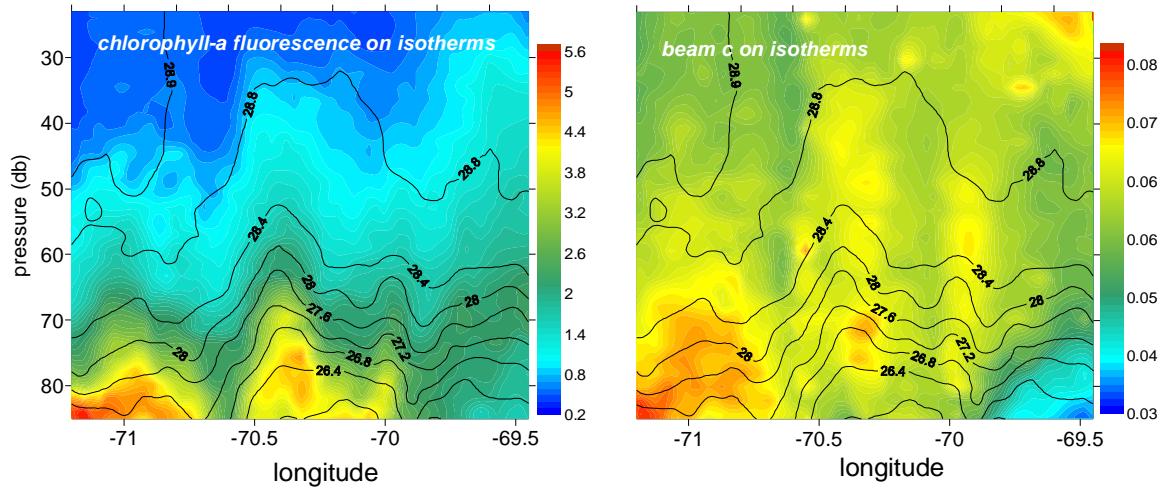


Figure 9. *UUV based isotherm contours of upper 90 m overlaid on chlorophyll-a fluorescence color map indicates the widespread occurrence (both within and outside of eddies) of vertical excursions in the 5 to 20 meter range with apparent wavelengths ranging from 4 to 15 km. Often these coincided with localized enhancement of chlorophyll and or decreases in beam attenuation coefficient (c 670).*

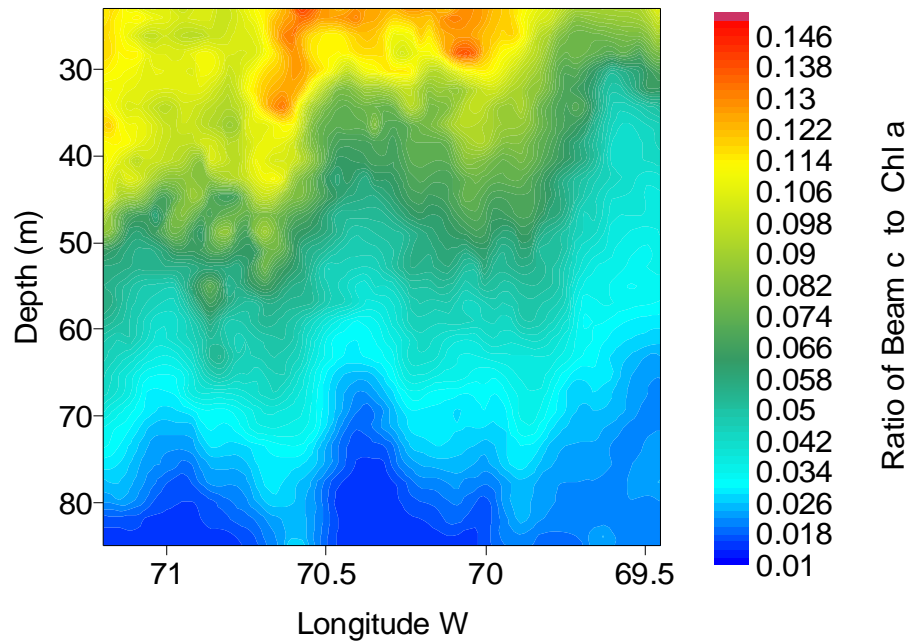


Figure 10. *The ratio of Beam c to Chlorophyll-a suggests surface accumulation of non-chlorophyll carbon in the cyclone core. Data indicates the widespread occurrence (both within and outside of eddies) of vertical excursions in the 5 to 20 meter range with apparent wavelengths ranging from 4 to 15 km. Often these coincided with localized enhancement of chlorophyll and or decreases in beam attenuation coefficient (c 660).*

E. Eddy pumping results

Apparent nutrient drawdown in a Caribbean Cyclonic Eddy

A fine-scale nutrient sampling pattern at selected isopycnals spanning the euphotic zone was undertaken across the cyclonic eddy depicted in Figure 11 in order to characterize nutrient drawdown attributable to eddy pumping. Our results show unequivocal drawdown of Dissolved Inorganic Nitrogen (DIN), and Dissolved Inorganic Phosphorus (DIP) across the eddy along its displacement path. In order to assess the magnitude of nutrient drawdown across the eddy, limiting calculations to depths above the compensation depth of 169 m, we determine the difference between observed mean concentrations at the two westernmost (presumably unaffected by eddy pumping) and easternmost stations across the eddy dome. We then integrate this across the entire eddy, arriving at total drawdown of 152 and 9 mmol.m⁻² DIN and DIP respectively. The drawdown ratio of DIN:DIP was 16.5 denoting a slight preferential DIN uptake over the canonical 15, agreeing with previous arguments of N limitation in the region. Given an eddy diameter of 186 km (deduced from isopycnal displacement) and an average westward displacement speed of 11.6 km.d (deduced from SSHA imagery), and assuming purely Eulerian displacement of the eddy across a static background, we calculate drawdown rates of 9.6 and 0.6 mmole.m⁻².d⁻¹ for DIN and DIP respectively, sufficient to sustain a primary production rate of 744-766 mgC.m⁻².d⁻¹ assuming Redfield stoichiometry. This rate is substantially higher than rates quoted for waters of the northern ECB 262 mg C.m⁻².d⁻¹ but lower than the exceptionally high rates observed, for example, in the upwelling regions of the southern margin of the Caribbean.

Apparent drawdown observed was the maximum possible within the eddy as we endeavored to implement the transect across the eddy core where isopycnal lifting is greatest. Since nutrient concentrations increase linearly with depth in the depth range immediately below the euphotic zone, diminished isopycnal lift towards the eddy margin will result in a commensurate depression of euphotic zone enrichment. On the other hand, eddy core SSHA anomalies ranged between -8 and -22 cm, standing at -12 cm during the time of our study. Eddy pumping might have been significantly greater during times of enhanced SSHA.

It is noteworthy that drawdown was incomplete and substantial residual nutrients (52 % DIP 43 % DIN) remained in the euphotic zone following passage of the eddy (station 22). Maximum efficiency of the eddy pumping process rests on the postulate that phytoplankton capacity for nutrient uptake is such that nutrients advected into the euphotic zone are entirely depleted within the time frame of eddy passage; on the order of 23 days in the SNA. Water masses advected from below the euphotic zone are largely devoid of phytoplankton so that seed populations are small. Moreover, greatest enrichment occurs in the deeper zones where light is a limiting factor. Phytoplankton uptake in our study appears to have been insufficient to allow complete nutrient stripping within the time frame of eddy passage, a result anticipated in previous studies. Incomplete drawdown and the uncertainties regarding drawdown across the slope of the eddy disallow estimation of total drawdown. Nevertheless, our results point to significant nutrient drawdown in this eddy.

Uncertainties regarding eddy pumping are due in large part to poor understanding of the underlying physics. Questions regarding net vertical transport of water parcels and hence of nutrient transport into the photic zone remain unsolved. This quandary has been summarized as the degree to which eddy propagation is linear or Eulerian rather than nonlinear or Lagrangian. In the latter, a water parcel is trapped within the eddy and nutrient contribution to the euphotic zone throughout the life of the eddy is limited to the content of that water parcel while in the linear case, favored by earlier models all

nitrogen in a theoretical ridge along the eddy track is made available. Larger “ring” structures, with diameters on the order of 500 km such as North Brazil current rings, Gulf of Mexico loop current eddies, Agulhas retroflection rings, and cold and hot core Gulf stream rings all appear to entail entrainment of water masses distinct to those of the eddy-generating current and advection of this parcel across various ocean fronts thus resulting in Lagrangian transport. Advected parcels typically exhibit reduced vorticity relative to an outer more vigorous ring arising from the original meandering current. Of these closed circulation systems, only cold core Gulf Stream rings are cyclonic and thus capable of eddy pumping. Entrainment and advection of a central water mass will significantly reduce eddy pumping as this water mass will be depleted of available nutrients at a time scale on the order of days relative to eddy lifetimes on the order of several months. In these structures, moreover, vorticity decays throughout the lifetime of the ring bringing about decay of the nutrient dome further precipitating the onset of oligotrophy.

Evidence is lacking regarding whether cyclonic eddies with diameters on the order of 200 km exhibit such Lagrangian transport or if, on the other hand, only energy, but no mass is advected laterally and water mass displacement is confined to transitory vertical advection during passage of the eddy. Such latter scenarios are presumed in eddy pumping models yielding highest estimates of photic zone fertilization where eddy passage is viewed akin to wave passage. More conservative, longer term models] take into account the necessary recharging of the subphotic nutrient zone, further reducing fertilization rate estimates.

Such simple models, moreover, portray eddy passage across an immobile background. Caribbean eddies on the other hand transit the region zonally accompanying the net westward transport of the Caribbean current. Surprisingly, average zonal current velocities may exceed net eddy transit rates. Using altimetry data, found that anticyclonic features that appeared near the Beata Rise (73° W) traveled westward into the Colombian Basin at an average speed of 15 cm s^{-1} . Because this is significantly slower than the speed of Lagrangian drifters, they suggest that these features are interacting with the mean Caribbean Current, not being passively advected by it. If this were the case then the nutrient drawdown we observe is in fact due to interaction of the eddy with fresh water masses.

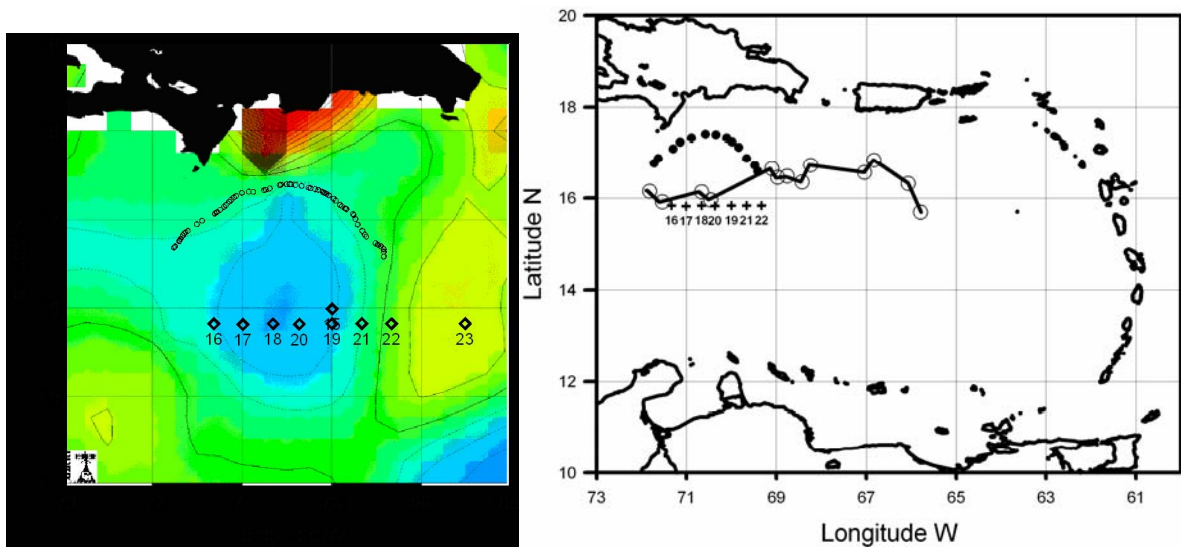


Figure 11. Right image shows drifter buoy circling cyclonic eddy. Left image shows eddy trajectory (open circles) as deduced from SSHA, first observation at 15.7° N 65.8° W 6/30/2006, last observation on 9/30/2006; buoy trajectory (closed circles), first observation at 16.9° N 68.6° W on 8/28/2006, last observation on 9/4/2006 and; station positions (crosses) first station on 9/05/2006, last on 9/08/2006.

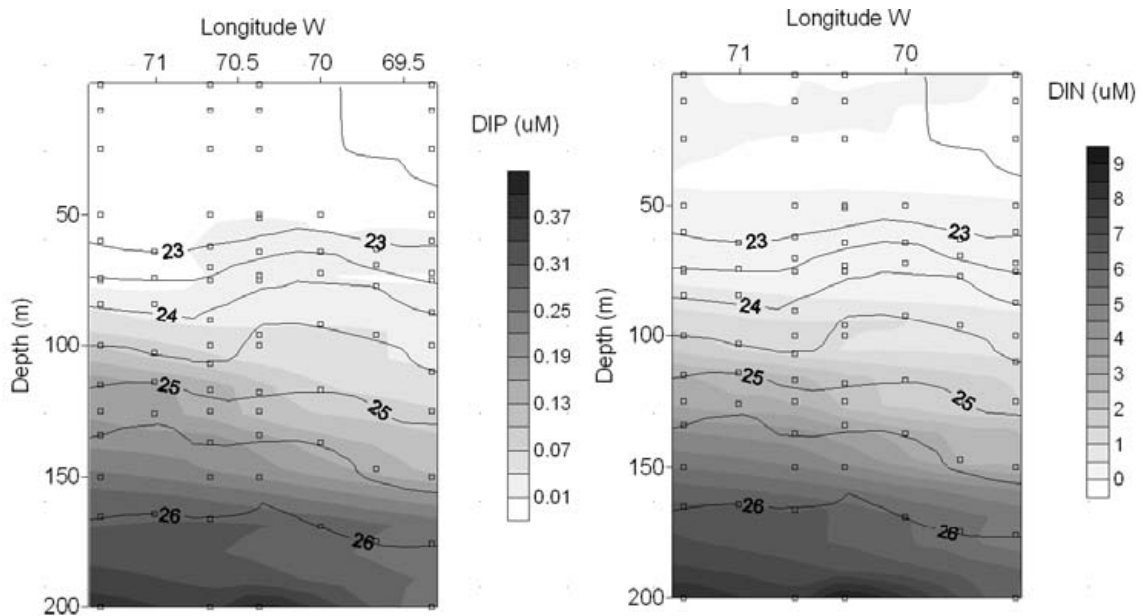


Figure 12. Density and nutrient sections across the cyclonic eddy along latitude 67.8° W. Isopycnals are represented by lines, nutrient fields as grayscale gradients. Left – DIN; right – DIP.

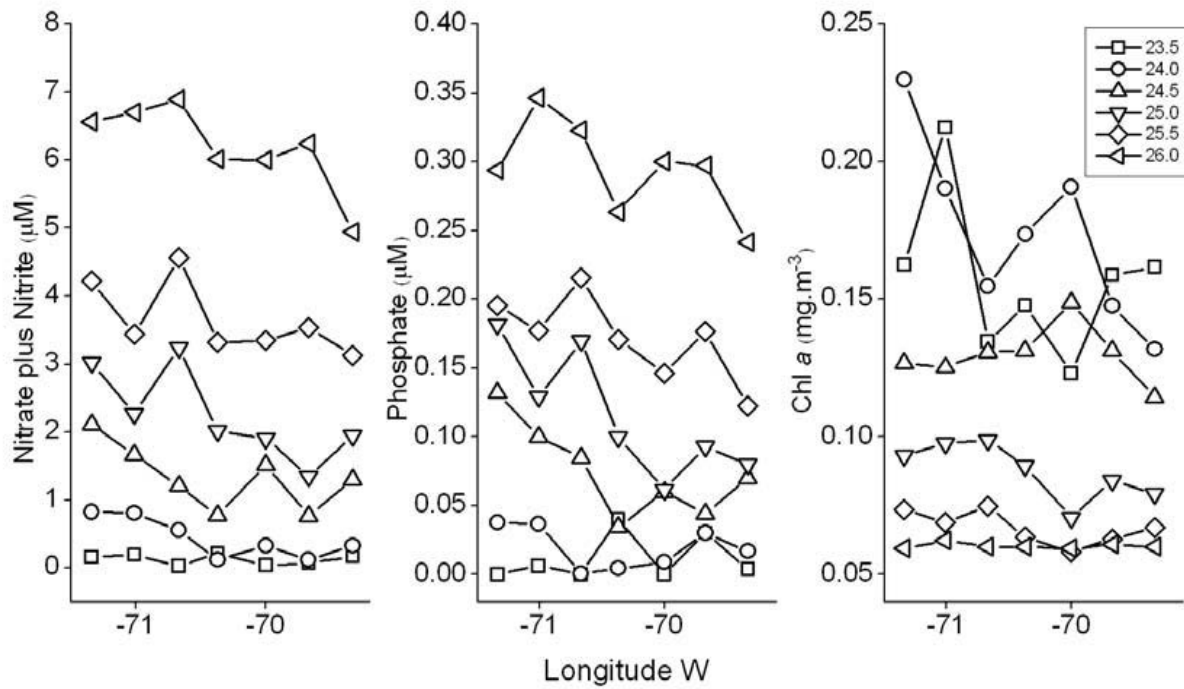


Figure 13. Nutrient loss and phytoplankton response along isopycnals in the transect across the eddy along 15° to 50°N. Left – DIN, center – DIP, right Chl a.

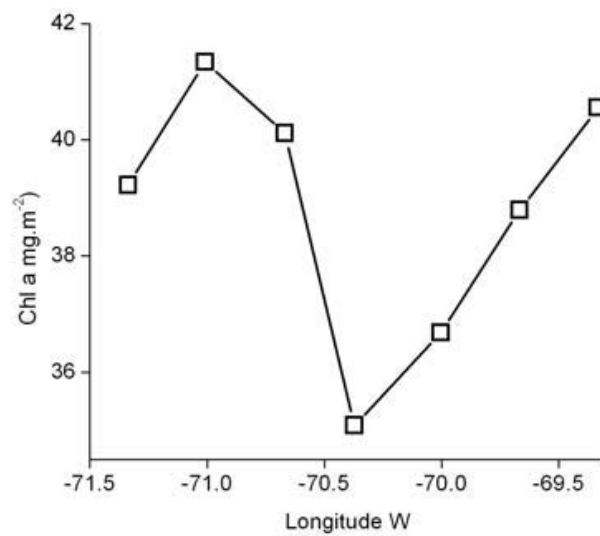


Figure 14. Integrated chlorophyll concentration (mg.m^{-2}) across the cyclonic eddy.

IMPACT/APPLICATIONS

Independent Temperature measurement profiles were made by CTD and XBT casts at nominally 30km horizontal intervals across a cyclonic eddy with nominal vertical resolution of less than 1 m. Meridional plots of eddy cross section from the interpolated data at this resolution show evidence of shallow doming of isotherms (Thermocline Eddy). A much more complex physical and optical structure is revealed by the 1 km horizontal resolution (< 1 m vertical) data obtained with the Undulating Underwater Data Collection System across the same transect of the Cyclonic eddy. Upper water column structure observed through this approach documented intricate excursions (high rugosity of the surfaces) of the upper thermocline, halocline and subsurface chlorophyll maxima beyond that expected from “classical” eddy doming alone. The ratio of Beam c to Chlorophyll-a suggests surface accumulation of non-chlorophyll carbon in the cyclone core. Data indicates the widespread occurrence (both within and outside of eddies) of vertical excursions in the 5 to 20 meter range with apparent wavelengths ranging from 4 to 15 km. Often these coincided with localized enhancement of chlorophyll and or decreases in beam attenuation coefficient (c_{660}).

Eddy pumping, a mechanism by which isopycnal doming in cyclonic eddies advects nutrient-rich water into the euphotic zone (EZ), is postulated to fertilize the euphotic zone enhancing phytoplankton production. In order to provide objective data on nutrient drawdown, we followed nutrient content along density surfaces across a cyclonic eddy in the eastern Caribbean Basin. We observed EZ drawdown of 152 and 9 mmol.m^{-2} dissolved inorganic nitrogen (DIN) and phosphorus (DIP) respectively across the eddy core. Based on an average eddy translational speed of 10 cm.sec^{-1} derived from satellite altimetry and assuming Eulerian displacement of the eddy across a static background, we calculate maximum possible drawdown rates of 9.6 and 0.6 $\text{mmole.m}^{-2}.\text{d}^{-1}$ for DIN and DIP respectively, sufficient to sustain a primary production rate of 766 $\text{mgC.m}^{-2}.\text{d}^{-1}$. Nutrient drawdown was however incomplete and residual nutrients (52 % DIP 43 % DIN) remained in the euphotic zone following passage of the eddy.

PUBLICATIONS

Morell J. M., López ,J.M, Méndez, M. and Corredor, J. E., “Optical Signatures of Mesoscale features in the Eastern Caribbean Basin” Poster, XVIII Ocean Optics Meeting, Montreal, Canada, (Oct 9-13, 2006).

López ,J.M, Morell J. M., Capella, J.and Corredor, J. E. “Caribbean Mesoscale Eddies” Poster, Ocean Sciences Meeting, Santa Fe, NM (Feb 8-12, 2007).

Corredor, J. E, Morell J. M. and López ,J.M, “Apparent nutrient drawdown in a Caribbean Cyclonic Eddy” Submitted to Geophysical Research Letters (2007)